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**CONCEPTUAL DESIGN OF A COMPACT FAST
REACTOR FOR SPACE POWER**

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TECHNICAL PAPER proposed for presentation at
American Nuclear Society National Meeting
Boston, Massachusetts, June 13-17, 1971

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FOR SPACE POWER

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SUMMARY

A technology program for a compact fast reactor for space power is in progress at Lewis Research Center. This paper presents program scope and objectives and introduces the reactor concept used to focus the program. Reactor performance goals are: life - 50,000 hours, coolant outlet temperature - 1220 K, thermal power ~ 2 Mw.

A fast reactor is smaller than a thermal reactor, reduces shield weight, and allows use of refractory metal structural material. The design concept is aimed at high reliability, reasonable dependence on advances in technology, growth potential in temperature and life, and flexibility in size.

Ceramic UN is the primary fuel candidate (UO_2 and UC were considered) because of high uranium content, thermal conductivity and melting point. Performance data for UN at temperatures and burnups of interest are available. Lithium coolant was chosen because of superior heat transfer characteristics and high temperature potential. Tantalum alloy, T-111, is a strong ductile and relatively easily fabricable refractory. It is the reference structural material with Nb-1Zr as back-up. Moving fuel is the preferred method for controlling the reactor. It is flexible and requires a minimum of new material technology. Data for cermet bearing materials operating in liquid metals exist. The seal required with moving fuel is the subject of one phase of our program. An alternative control is B_4C in passively cooled rods. Unknown behavior of B_4C and possible requirement for high emissivity coatings are negative aspects of this approach.

The reference design contains 247, 1.90 cm diameter, fuel pins with a fuel length of 37.6 cm. The fuel elements were designed for < 1 percent diametral growth using applicable analytical techniques. Salient features of the design shown include stationary core fuel elements, 6 rotating drums containing fuel, molybdenum alloy (TZM) reflectors, and a honeycomb fuel element support structure. This consists of thin walled T-111 tubes bundled and welded along lines of contact by procedures recently developed. It supports the elements, limits their bowing and provides an annular flow passage around each element. This approach results in low hot spot factors at some sacrifice in core size. Lithium flows through the entire pressure vessel in one pass with a ΔT of 55.3 K. The cermet drum bearings are mounted in pressure vessel nozzles. Lithium is sealed in the drum drive train by a nutating rod device incorporating a flexing bellows. The dry portion of the drive includes scram spring, latching devices, harmonic drive and stepping motor.

Dynamic analysis of a system using this reactor with Brayton power conversion indicates slow, stable response to perturbations in reactivity and flow rate of coolant and working fluid. Investigation of typical malfunctions show that loss of coolant is the only one posing a serious problem. Prompt criticality can be avoided by limiting drum reactivity insertion rates to 8 cents/sec.

INTRODUCTION

A technology program for a compact fast reactor for space power is being carried out at Lewis Research Center. The thrust of the program is to identify general problem areas associated with this type of reactor and to undertake analytical and experimental investigations leading to development of designs, procedures, and techniques that will provide satisfactory solutions. An evolving reactor concept serves to focus our technology program. This concept incorporates on a current basis ideas of the best approach to such a reactor. This paper presents the scope and objectives of the technology program and introduces the reference reactor concept.

A fast reactor was chosen rather than a thermal reactor because it reduces size and shield weight (Ref. 1). It also has the advantage of the use of refractory metal structural material. The principal disadvantages lie in sensitivity to fuel element motion, control limitations, and the consequences of a loss of coolant accident.

The reactor performance goals have been established as follows:

Life	50,000 hours
Coolant outlet temperature	1220 K (1740° F)
Thermal power	~ 2 MW

The additional criteria for the concept include high reliability with reasonable dependence on advances in technology. Reactor concepts sometimes fail to reach fruition because they are predicated on quantum steps in technology. On the other hand, one goal of the reference reactor concept is that its salient features will still be valid and applicable for different operating requirements such as temperature, power and life. Growth potential then is an important criterion in the reactor concept.

Once the generic problems inherent in this type of reactor were uncovered by design studies, investigative programs were established to explore these problems. Areas of primary concern include materials, fuel element and core support structure, reactor physics and reactor control. Materials work includes compatibility, mechanical properties before and after irradiation, and processing. Fuel element investigations cover analysis of swelling, inpile testing, and environmental testing. Reactor physics effort has included critical assembly experiments, cross section measurements and reactor modeling. In the area of reactor control, dynamic analysis is being carried out to establish control component requirements and basic components are being built and tested. Safety studies are also being carried on in conjunction with the control system work.

The remainder of this paper will deal with a description of the reference reactor and a discussion of some of the work done in the non-nuclear areas. (Refs. 2 and 3 discuss other areas of the program.) In aspects where considerable uncertainty exists about successful operation, alternatives have been generated and associated technology is included in the program. These alternatives will also be discussed.

DISCUSSION OF CONCEPT

A. Selection of Fuel, Coolant, and Structural Materials

The field of fuel, coolant, and structural material candidates was necessarily limited because of the high temperature and the desire to minimize reactor size. Therefore, priority was given to high strength refractory materials. The fuel candidates were restricted to ceramics (UN, UO_2 and UC), the coolants considered were liquid metals (Li, Na, K, NaK), and the structural materials were limited to the refractory metals (alloys of Ta, W, Mo, and Nb). A comparison of some of the important characteristics of the fuel and coolant candidates is presented in Table I. Uranium mononitride was selected as the primary fuel candidate because of its high uranium content, high thermal conductivity, and high melting point. UN contains about 40 percent more fissionable material per unit volume than UO_2 and about 5 percent more fissionable material per unit volume than UC. The higher uranium content of UN results in a smaller critical reactor configuration. The thermal conductivity of UN is about ten times better than UO_2 and about 4 percent better than UC. The melting point of UN is several hundred degrees higher than UC. Fuel swelling was recognized as a potential problem area for all fuel candidates. However, some irradiation performance data for UN at temperatures and burnups of interest are available (Ref. 4). These data indicate that the fuel volume swelling under these temperature and burn-up conditions is reasonable.

Work on the fabrication of high purity UN fuel forms has been carried out at Oak Ridge National Laboratories (Ref. 5). Cylinders, both hollow and solid, have been routinely produced by isostatic pressing and sintering a fine powder of UN.

Lithium was selected as the primary coolant candidate because of its low vapor pressure, high specific heat, low pumping power requirements, and high heat transfer coefficient (Ref. 6). The low vapor pressure allows lower operating pressures in the system resulting in greater reliability and reactor growth potential. The larger specific heat of lithium allows maintenance of a given coolant temperature rise with a lower coolant flow, lower pressure loss and lower pumping power requirements (a factor of 8.5 lower pumping power for lithium than sodium). All of the liquid metal coolant candidates have large thermal

conductivities resulting in high convective heat transfer coefficients. However, lithium has 15 to 40 percent higher film coefficient than the other liquid metal coolants. Potential disadvantages of liquid metals considered for coolants are their toxicity and chemical activity. The Li-7 isotope must be used to obtain a negative temperature coefficient of reactivity and to minimize the production of gaseous decay products. Lithium containing 99.99 percent Li-7 can be obtained for about \$1.00 per gm. The reactor loop will require about 30 kg (66.0 lb) of lithium.

The tantalum alloy T-111 (Ta-8W-2.4 Hf) was selected as the primary structural material candidate because of its strength and ductility (Ref. 7). The alloy Nb-1Zr was selected as an alternate. Both alloys are ductile (elongation to failure greater than 15%), easily fabricable relative to the other refractories, and are compatible with the lithium coolant at the temperatures of interest. However, a protective tungsten liner may be required between the fuel and clad to minimize any chemical reaction between the fuel and clad. The creep and rupture strengths of T-111 and Nb-1Zr are shown in Fig. 1 (Refs. 7 and 8, respectively) as a function of the Larson-Miller Parameter, P . The creep and rupture strengths of T-111 at operating conditions ($P = 24.7$) are 6 and 4-1/2 times greater than Nb-1Zr. Because of this, the T-111 alloy offers greater growth potential (increased operating temperature or longer life). A potential disadvantage of T-111 is its affinity for impurities such as hydrogen and oxygen which cause embrittlement and loss of rupture strength. These characteristics of T-111 are being investigated and the program is discussed in Ref. 2.

B. Selection of Control System

Several methods of controlling the reactor were investigated and are discussed in Ref. 3. A moving fuel concept (fueled control drum) was selected as the primary method of control because it allows the smallest reactor for the specified design conditions. However, special problems are encountered with this concept. Because much of the reactor power is generated in movable control drums (see Fig. 2), they must be cooled with reactor coolant. This means that high temperature, lithium lubricated bearings must be selected, and a moving lithium-to-vacuum seal must be designed.

C. Selection of Bearing Material

There has been considerable work done on bearings operating in high temperature liquid metals. Refs. 9 and 10 report satisfactory behavior in liquid sodium and liquid potassium to temperatures of 1144 K (1600° F). These results indicate that very hard materials are required. The reactive lithium environment would require a high degree of chemical stability.

Bearing material candidates considered for this reactor concept are the refractory ceramics HfN, HfC, ZrC, ZrN, NbC and TaC with molybdenum or tungsten bond. Chemical stability testing of cermet containing various combination of these materials is presently being carried out and is briefly discussed in Ref. 2. Based on early results and on fabrication experience, density, grain size, distribution of metal bond and other factors, HfC + 8w/o M + 2w/o NbC appears to be the most promising candidate. HfN + 10 w/o W is considered as a back-up. Bearings of these materials are being made and will be tested.

D. Selection of Penetration Device

Another area which must be examined when considering a moving fuel control concept is the penetration through the pressure vessel required in the drum drive system. These penetrations must form an hermetic seal for the reactor coolant. One device which will provide the required movement and seal is a nutating rod concept with flexing bellows forming the seal. Some details will be given later.

The cyclic life of bellows is often difficult to predict. In this application the problem is further complicated by the operating temperature, the presence of lithium and creep resulting from long hold times in the flexed position. It is planned to make the bellows of T-111 sheet. Analytical predictions of cyclic life taking creep into account have been made and fatigue tests of sheet material are in progress. Short hold time tests to date indicate greater than predicted life.

Preliminary forming trials of T-111 bellows were successful. Equipment for the testing of bearings and bellows at elevated temperature in lithium is being fabricated.

DESCRIPTION OF REACTOR

The reference reactor configuration is shown in Fig. 2 and some of its important characteristics are listed in Table II. The components include fuel elements, core support structure, end and side TZM (Mo-0.5Ti-0.1Zr) reflectors, control drums, and penetration devices. All are enclosed in a pressure vessel which is about 57.7 cm (22.7 in.) in diameter and 68.5 cm (27 in) long overall. The lithium coolant flows through the vessel in one pass cooling all the components.

A. Mechanical Components

The 247 fuel elements are 1.90 cm (0.75 in.) in diameter with a clad thickness of 0.147 cm (0.058 in.), see Fig. 3. The fuel length is 37.6 cm (14.8 in.) and a 0.013 cm (5 mil) tungsten barrier is provided

between the fuel and clad to prevent possible interaction. Vibration suppressors are located at each end of the fuel pin. These are designed to reduce axial clearance between fuel and clad so that launch vibrations can be tolerated and to buckle when the fuel expands due to temperature and burn-up. These end spaces will accommodate fuel swelling and released fission gas. The fuel pellets are hollow and the central hole serves this same function of providing space for fuel swelling and gas release. Fuel pellets were subjected to typical launch vibration environments to check the effects on pellet cracking of diametral and axial clearance with the clad. Relatively large diametral gaps could be tolerated but the axial gap was quite critical. Tests also indicate that the buckling action of the suppressor under vibration is also sensitive to axial clearance.

One hundred and eighty one of the fuel elements are stationary and are held by the core support structure identified in Fig. 2. It consists of a central star-shaped assembly of thin tubes and a reinforced flange joining the tubes to the pressure vessel. Its main function is to locate the fuel pins axially and radially and to limit fuel pin bowing. It also provides an annular coolant passage around each fuel pin. Fig. 4 illustrates how these functions are performed and shows a portion of the honeycomb tube structure. The tubes are T-111, 2.160 cm (0.850 in.) outside diameter and have a 0.025 cm (10 mil) wall. The tubes are joined to each other by welding along their lines of contact. The result is a very stiff structure for carrying axial loads and resisting thermal distortion. A bayonet joint in a plate welded to one end of the tube cluster provides axial support for each fuel element. A locking device at the opposite end of the tubes prevents element rotation but allows axial growth.

Each tube has five internal rings or inserts approximately equally spaced along its length. Each insert contains three internal projections, formed and filled with weld metal. They are finish machined after welding of the entire assembly is complete. The two sets of projections at the end of the tubes engage closely machined diameters on the fuel element end caps thereby providing radial location. No diametral growth of the fuel element should occur at these locations. The three interior sets of projections on the tubes are machined for clearance with the element clad to allow for expected growth. They do, however, limit fuel pin bowing to this clearance at beginning of life and to progressively smaller amounts as clad growth occurs. Bowing limitation is important for reducing reactivity changes due to shifting fuel and for stabilizing the geometry of the annular flow passage between each fuel element and the honeycomb tube. Flow through the trifiutes of the honeycomb is kept low by orifice holes in the end plate.

Fabrication studies for the honeycomb support structure are underway and early results are reported in Ref. 11. Success has been achieved in making tube-to-tube and tube-to-end plate joints using tungsten inert

gas welding. Electron beam welding has been successfully used for tube-to-insert joints. Work is presently concentrating on reducing radial distortion due to tube-to-tube welds.

Outside the tube cluster portion of the core support structure are the side reflector pieces and six control drums as shown in Fig. 2. The main portion of each drum is molybdenum alloy TZM like the reflectors. Each drum also holds 11 fuel elements and a region of T-111 which acts as a neutron absorber. In the shut-down position the T-111 is adjacent to the core as the drum is rotated fuel replaces absorber next to the core and reactivity is increased. The drum rotates through 180° .

The drum shaft rides in two cermet bearings designed to accommodate misalignment and one takes thrust. Each is located in a nozzle extension on the pressure vessel heads. This would permit reducing bearing temperature with a small subcooled lithium flow loop should that become necessary. A vane type hydraulic dashpot using lithium coolant as the fluid is included to decelerate the drum at the end of scram.

The penetration device shown is a variation of a nutating rod type of device commonly used to transmit rotary motion through a seal provided by a bellows. The bellows is required to bend in a rotating plane but does not rotate about its axis as the motion is transmitted. This design uses two bellows for redundancy. There are several bearings in this device. Those operating in lithium are cermets like the drum shaft bearings. Those outside the seal are graphite- Al_2O_3 similar to those developed for the SNAP-8, ZrH, reactor.

B. Fluid Flow and Heat Transfer

Typical heat transfer and fluid flow characteristics for the reference reactor are summarized in Table II. The reactor is cooled in a single pass with a flow of 9.4 kg/sec (20.7 lb/sec) of liquid lithium. About 10 percent of this cools the side reflector (see Fig. 2) and about 6 percent is distributed among the triffutes (see Fig. 4) to prevent stagnant lithium from collecting in these regions. The remaining 84 percent of the coolant is equally distributed (within 1%) among the 247 fuel pins. The coolant flows through an annular passage (equivalent diameter = 0.10 cm (40 mil)) between the honeycomb tube and the fuel pin at a velocity of 115 cm/sec (3.8 ft/sec). The irreversible pressure loss from plenum-to-plenum is about 0.7 N/cm^2 (1.0 psi). The minimum pressure and lithium saturation temperature are 13.8 N/cm^2 (20 psi), 1650 K, (2510° F) respectively. A full scale hydraulic model of a fuel pin and honeycomb tube using water as a fluid has been fabricated and tested. Total measured pressure losses agreed within 10 percent of the calculated values.

Some degree of radial power tailoring is incorporated to make fuel swelling somewhat uniform. Three radial fuel zones having progressively

higher fuel contents are obtained by reducing the size of the hole in the center of the fuel pellets which are further from the center of the reactor. The resulting radial and axial power factors (not critical) are 1.33 and 1.23, respectively. The average heat flux in the reactor is 39 w/cm^2 ($1.24 \times 10^5 \text{ Btu/(hr)(ft}^2)$). The Peclet number (70) is well below the critical Peclet (300) for annuli (Ref. 12). The average convective film coefficient calculated using Dwyer's correlation for annuli (Ref. 13) is about 17 w/cm^2 ($3.00 \times 10^4 \text{ Btu/(hr)(ft}^2)(^\circ\text{F})$). A typical fuel pin axial temperature distribution is shown in Fig. 5. Because of the large convective film coefficient and excellent conductivity of the T-111 clad, the clad temperature is nearly equal to the coolant temperature. Therefore, the maximum clad temperature (1250 K) (1790° F) occurs at the coolant outlet end of the reactor while the maximum fuel temperature occurs between the midplane and the coolant outlet end. The maximum fuel temperature excluding hot spot factors is 1370 K (2005° F). An estimated hot spot factor of 1.4 increases the maximum fuel temperature to 1450 K (2150° F). The primary contributor to this hot spot factor is the uncertainty in the initial size of the gap between the fuel and clad.

C. Fuel Swelling

One of the primary concerns in the design of the fuel pins for this reactor is the extent of fuel swelling and clad creep. A limit of 1 percent was set for clad diametral strain to avoid flow perturbations and allow for possible radiation embrittlement. There are many different swelling mechanisms which have been postulated recently and many mathematical models to describe these mechanisms. The two models which have been most used at Lewis Research Center to study the UN, T-111 system are based on work done by Lietzke (Ref. 14) and the CYGOR-2 program developed by Friedrich and Guilinger (Ref. 15) and later modified by Fiero (Ref. 16). These models emphasize behavior determined by stationary fission product gas bubbles. Post irradiation photomicrographs (Ref. 4) of UN fuel subjected to temperatures and burnups comparable to those anticipated in the reference reactor indicate a large portion of the fission gases remain within the UN grains. These data lend confidence to the use of such models of swelling behavior.

A typical fuel swelling curve calculated using the CYGOR-2 program is shown in Fig. 6. After initial startup, the fuel tends to sinter. The extent of sintering depends on the type of fuel, fabrication history and operating conditions. Some preliminary sintering experiments for about 3000 hours and 1310 K (1900° F) have been conducted and the results are being analyzed. As burnup progresses sufficient fission gases will be generated and the fuel will swell freely (free swelling) until it contacts the clad. If the clad has sufficient creep strength (as in the case of T-111), the clad will restrain the fuel causing a reduction in the fuel swelling rate and a redistribution of creep strain. The volumetric swelling and clad creep strains were calculated (Ref. 17) for 5 UN fuel pins clad with

either T-111 or PWC-11 (Nb-1Zr-0.1C) and the results are shown in Fig. 7. These fuel pins operated at temperatures and burnups comparable to those in the reference reactor. The rectangles represent uncertainties in calculated and measured values and the type of clad is shown. The calculations tend to be conservative and agree with measurements within about 60 percent.

The maximum fuel swelling in each of the three zones was calculated using the CYGRO-2 program and the results are summarized in Table III. The maximum fuel swelling (11.1%) and burnup (4.2%) occur in the center of the reactor (Zone I) and become progressively less through Zones II and III. The maximum diametral and axial creep strains, however, occur in Zone III. Although the fuel swelling is greater in Zone I, the hole in the center of the fuel is larger and the fuel structure is weaker allowing the clad to force fuel into the center hole. The result is 0.17 percent diametral creep strain in the clad in Zone I relative to 0.29 percent in Zone III. If ideal fuel zoning had been achieved, the diametral creep strains would be the same in all three zones. The maximum axial creep strain ($\Delta L/L$) in the clad is only 0.05 percent. Based on the calculated creep strains, this fuel pin design is conservative because the maximum creep strain (0.29%) is much less than the 1 percent value allowed as a design limit. This conservative fuel pin design allows for reactor growth potential.

Calculations were also made on the same fuel pins clad with Nb-1Zr instead of T-111. The maximum swelling and clad creep occurs in Zone I. Both the diametral and axial creep strains in the Nb-1Zr clad (2.3% and 4.0%) exceed the 1 percent strain limit. Therefore, a thicker clad would be required probably resulting in a larger reactor configuration and a loss in design conservatism.

These calculations also illustrate the effect of clad creep strength on swelling. The stronger T-111 clad suppressed the UN volume swelling by 3 percent (14.1% vs 11.1%). The suppression of fuel swelling by strengthening the clad has been observed experimentally (Ref. 18) by increasing clad thickness.

D. Alternate Control Concept

A concept which avoids the liquid metal lubricated bearings as well as the penetration device problem of the moving fuel control approach is also being studied. It is shown in Fig. 8.

In this concept rods containing B_4C are positioned within the core of the reactor, but not in contact with the reactor coolant. The rods are about 3.757 cm (1.478 in.) diameter overall including clad, with a gap between the rod outside diameter and the inside diameter of the dry

well provided for the rods in the pressure vessel. At the start of life the rods extend about a third of the way into the fueled section of the core. They are cooled by radiation to the lithium flowing outside the wells. The inside of the wells and the rods are exposed to space vacuum. Graphite- Al_2O_3 bearings can be used to guide the rods. There are 12 rods located in the core and each rod replaces 7 fuel pins so that the core diameter is slightly larger for this concept.

Heat transfer analyses have been made in order to establish the temperature levels in and around the B_4C rod. These analyses indicate that high emissivity coatings may be required on the outer wall of the B_4C rod and the surrounding wall of the well inside the pressure vessel in order to keep the temperature of the B_4C at reasonable levels. As an example, for an emissivity of 0.8 the maximum B_4C temperature is about 1330 K (1880° F); for an emissivity of 0.2 the maximum B_4C temperature is 1600 K (2419° F). If coatings are required their compatibility with surrounding structure and behavior in high radiation levels must be investigated. Since little is presently known about B_4C behavior at high temperature and fluences, allowable operating temperatures cannot be determined. Further information required includes:

1. Compatibility with other reactor materials.
2. Helium gas release rate.
3. Swelling
4. Mechanical properties

The unknown behavior of B_4C and the possibility of requiring high emissivity coatings are the primary drawbacks in this alternate approach to reactor control.

E. System Dynamics

Analysis of the dynamic behavior of the primary loop of a space power system using this reactor with Brayton conversion equipment has been performed (Ref. 19). The transient response of this loop, with a passive reactor control system, to changes in reactivity, coolant flow rate, and Brayton working fluid flow rate is stable and highly damped.

The response of the reactor to four malfunctions has also been investigated (Refs. 20 and 21). Control drum run-in, decrease in coolant flow rate, decrease in coolant inlet temperature, and loss of coolant accidents all resulted in relatively slow thermal response of a reactor with an inactive control system. The control drum run-in event at cold conditions indicate that prompt criticality can be avoided if the reactivity insertion rate of the drum drive is limited to 8 or 9 cents per second. This limit seems reasonable in view of the inherently slow

thermal response of the reactor to perturbations. Fig. 9 shows the behavior of average midplane fuel element temperature as a function of time after flow rate ramps of 1 second duration to various reduced flows. Even the drop-to-zero-flow accident results in a 30 second lapse time for the fuel temperature to reach 1610 K. (2440° F) the temperature at which nitrogen reaction with the clad material may become significant. Even longer reaction times resulted from a 20 percent decrease in coolant inlet temperature. The loss of coolant accident results in initial reactor shutdown but is the most severe one for this reactor because after-heat makes possible fuel melting and subsequent severe excursions.

More sophisticated analyses of this accident have continued taking into account such factors as heat capacity of shielding and the latest results are shown in Fig. 10. With a surface emissivity of 0.2, the melting point of the UN in the central pin is reached slightly over 1/2 hour after coolant loss and approximately 27 percent of the fuel in the core will reach its melting point as time goes on. Although this involves only about enough fully enriched uranium to ideally form a critical mass, it would be highly desirable to eliminate the possibility of any fuel melting. There are several potential techniques for accomplishing this. One is to increase surface emissivity of the fuel elements and core support structure. Fig. 11 shows that a surface emissivity of 0.4 results in no fuel melting. Other methods involve auxiliary heat sinks. These could be of low capacity since the reactor power at times greater than one hour is down to less than 2 percent of full power and only a fraction of the core is involved in potential melting.

CONCLUDING REMARKS

Progress to date on the technology program being conducted at Lewis Research Center for a compact fast reactor for space power indicates the following with respect to the conceptual design:

1. The fuel element design appears to be conservative from the standpoint of clad strain.
2. Substituting the back-up Nb-1Zr clad directly for T-111 does not satisfy the strain criterion. An increase in thickness is required which may affect core size and clad strain design margin.
3. The fabrication of a honeycomb core support structure designed to limit fuel element bowing appears feasible.
4. The heat transfer conditions are such that reasonable perturbations in coolant flow rate, fuel element geometry and power generation have small effect on fuel temperature.

5. The moving fuel control concept involves two major problems; high temperature bearings operating in lithium, and high temperature bellows seals.

6. Temperature operating limits for the B_4C in the alternate control system must be established. The results may indicate that a reliable high emissive coating is required for satisfactory operation.

7. The thermal response of the reactor to various perturbations indicates no unusual control system requirements.

8. The only accident which poses a particular problem is loss of coolant. Some reliable method for coping with this must be generated.

These results are based on information from only a portion of the planned program. Extensive testing and analysis remains to be completed to fully explore problems and their possible solutions.

TABLE I
COMPARISON OF FUELS AND COOLANTS

<u>Fuels</u>	<u>UN</u>	<u>UO₂</u>	<u>UC</u>	
Uranium density, g-U/cc fuel	13.5	9.67	12.9	
Thermal conductivity, W/cm K	0.24	0.025	0.23	
Melting point, K	3073	3078	2623	
<u>Coolants</u>	<u>Li</u>	<u>Na</u>	<u>NaK</u>	<u>K</u>
Vapor pressure @ 1220 K, N/cm ² (psi)	0.3(0.5)	17(25)	28(40)	48(70)
Specific heat, J/Kg K	4170	1290	1060	833
Relative pumping power	1.0	8.5	17	42
Relative convective film coefficient	1.0	0.85	0.60	0.65

TABLE II

COMPACT FAST REACTOR CHARACTERISTICSGeneral

Reactor power, MW	2.17
Operating life, hr	50,000
Coolant inlet temperature, K	1165
Average coolant outlet temperature, K	1222
Number of fuel pins	247
Fuel pin diameter, cm	1.90
Active core length, cm	37.6
Fuel loading, Kg U-235	182
Total weight of reactor	1600

Reactor Structure

Material	T-111
Pressure vessel O.D. cm	57.7
Pressure vessel wall thickness, cm	0.635
Pressure vessel height, cm	68.5
Honeycomb structure tubes - O.D., cm	2.16
Honeycomb structure tube wall thickness, cm	0.025

Fuel Pin

Composition	UN
U-235 enrichment, %	93.2
Clad material	T-111
Fuel pin O.D., cm	1.90
Fuel pin length, cm	43.8
Clad thickness, cm	0.147
Tungsten liner thickness, cm	0.013
Fuel pellet O.D., cm	1.58
Nominal radial fuel-clad gap, cm	0.011
Active fuel length, cm	37.6

Fluid Flow

Coolant	Li
Mass flow, Kg/sec	9.4
Fraction of flow to side reflector	0.10
Fraction of flow to triffutes	0.06
Equivalent diameter of coolant annulus, cm	0.102
Coolant velocity in annulus, cm/sec	115
Reynolds number in annulus	4500
Plenum-to-plenum Δp , N/cm ²	0.7
Minimum coolant pressure, N/cm ²	13.8
Saturation temperature of Li at 13.8 N/cm ² , K	1650

TABLE II (continued)

Heat Transfer

Radial power factor (beginning of core life)	1.33
Axial power factor	1.23
Average heat flux, W/cm ²	39
Peclet number	70
Average convective film coefficient, W/cm ² - K	17
Maximum clad temperature, K	1250
Maximum nominal fuel temperature, K	1370
Maximum fuel temperature (hot spot factor = 1.4), K	1450

Neutronic Design

onic Design

Neutron flux	1.02x10 ¹⁴			
Neutron flux (for energies > 0.82 ev)	0.35x10 ¹⁴			
Core composition volume fractions				
Zone	I	II	III	Avg
Fuel	0.355	0.377	0.420	0.385
Void	0.134	0.112	0.069	0.104
Structure + clad	0.259	0.259	0.259	0.259
Coolant	0.252	0.252	0.252	0.252

Control System

Materials	TZM, T-111, UN
Number of control drums	6
Number of fuel pins per drum	11
Drum O.D., cm	14.6
Drum length, cm	55
Reactivity worth of drums, percent $\Delta k/k$	
(a) Fuel & structure expansion	-0.58
(b) Coolant expansion	-0.26
(c) Doppler	-0.25
(d) Burnup	-1.47
(e) Axial fuel swelling	-0.95
(f) Contingency	-0.61
(g) 2-Stuck drum requirement	-4.39
Total	-8.51

Reflectors

Materials	TZM
Side reflector thickness, cm	~7.6
End reflector thickness, cm	5.08

TABLE III
 MAXIMUM FUEL PIN SWELLING IN 50,000 HOURS
 (CALCULATED WITH CYGRO-2)

Zone	Fuel ID, cm	Burnup, %	Clad mat'l.	Fuel	Clad	
				$\Delta V/V$, %	$\Delta D/D$, %	$\Delta L/L$, %
I	0.762	4.2	T-111	11.1	0.17	0.03
II	0.677	3.7	T-111	8.9	0.23	0.04
III	0.480	2.6	T-111	4.4	0.29	0.05
I	0.762	4.2	Nb-1Zr	14.1	2.3	4.0

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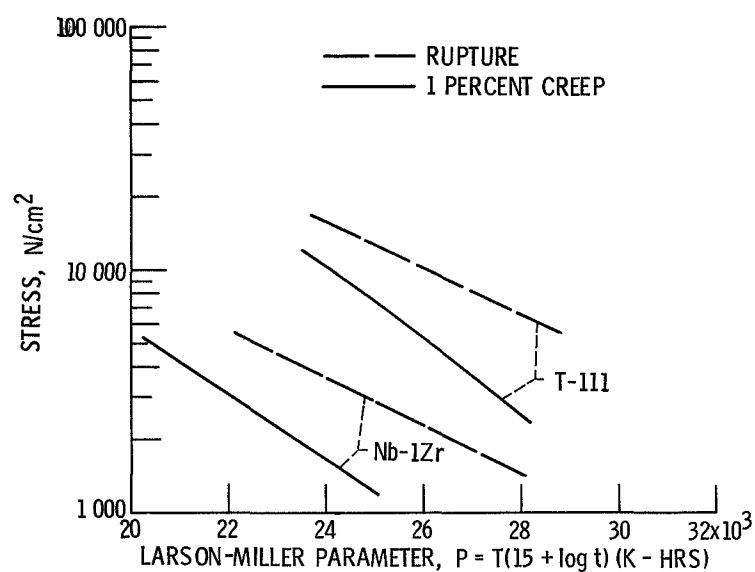


Figure 1. - Creep and rupture properties of T-111 and Nb-1Zr.

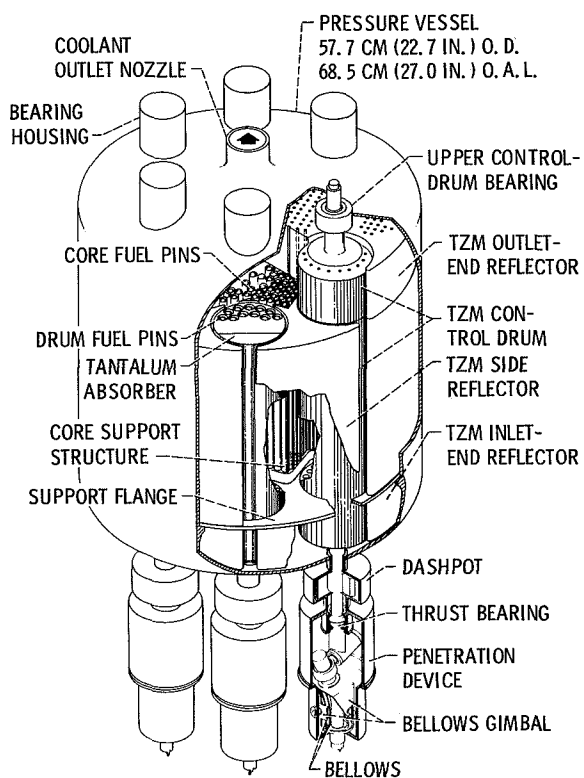


Figure 2. - Compact fast reactor-reference design.

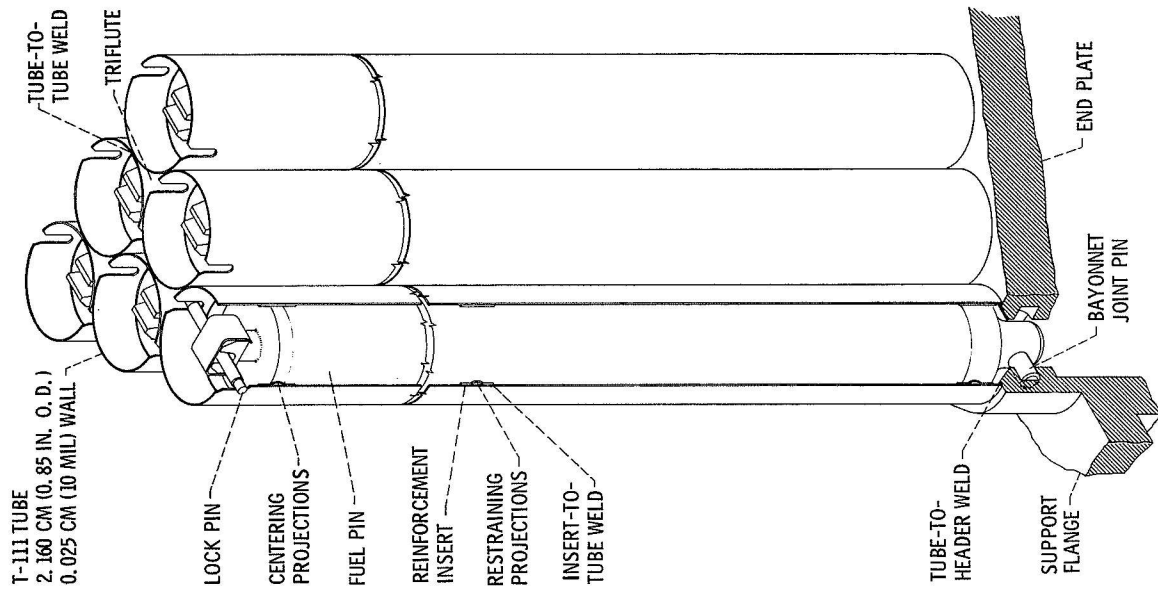


Figure 4. - Core support structure-Honeycomb concept.

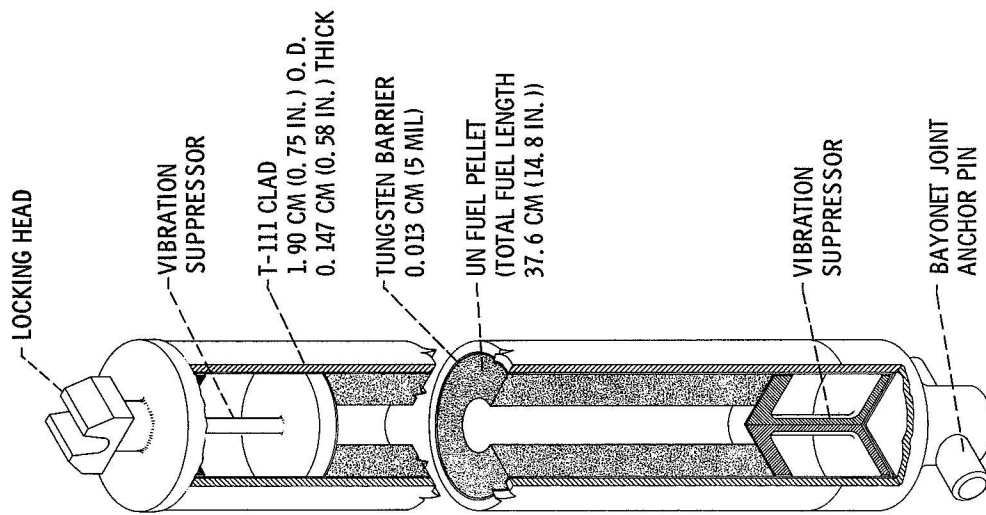


Figure 3. - Fuel element.

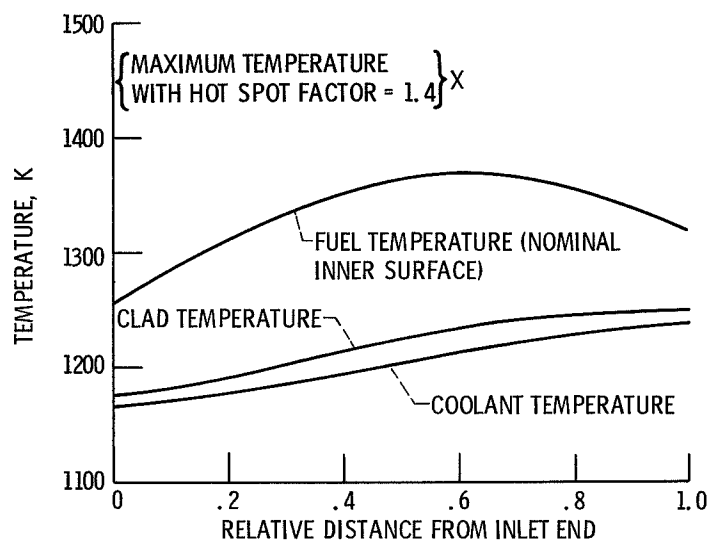


Figure 5. - Temperature distribution in hottest fuel element.

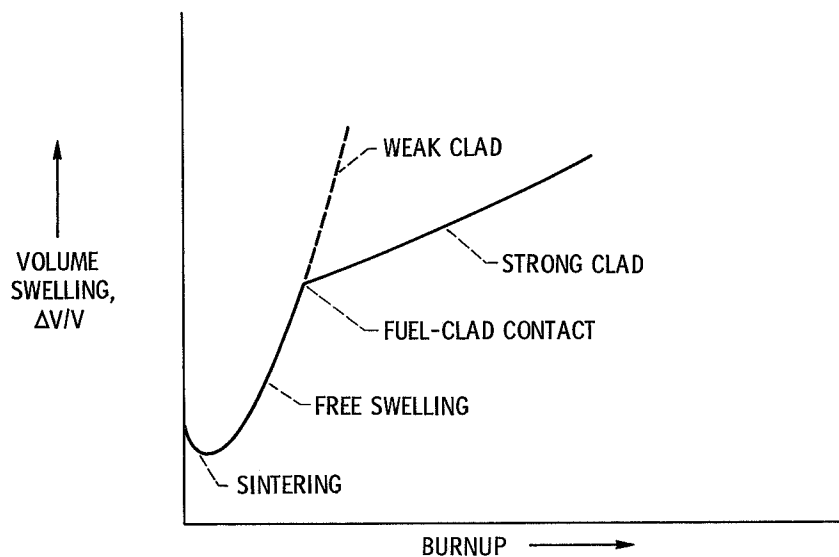


Figure 6. - Typical fuel swelling history (calculated).

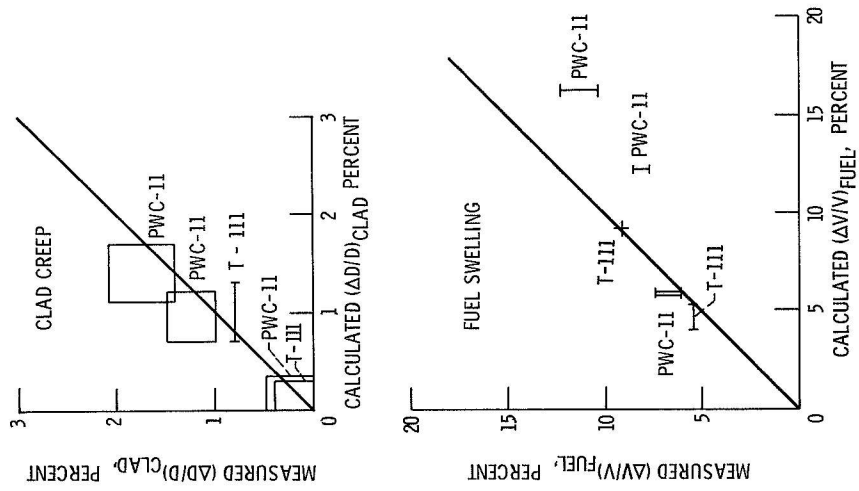


Figure 7. - Comparison of measured and calculated fuel swelling (ORNL data).

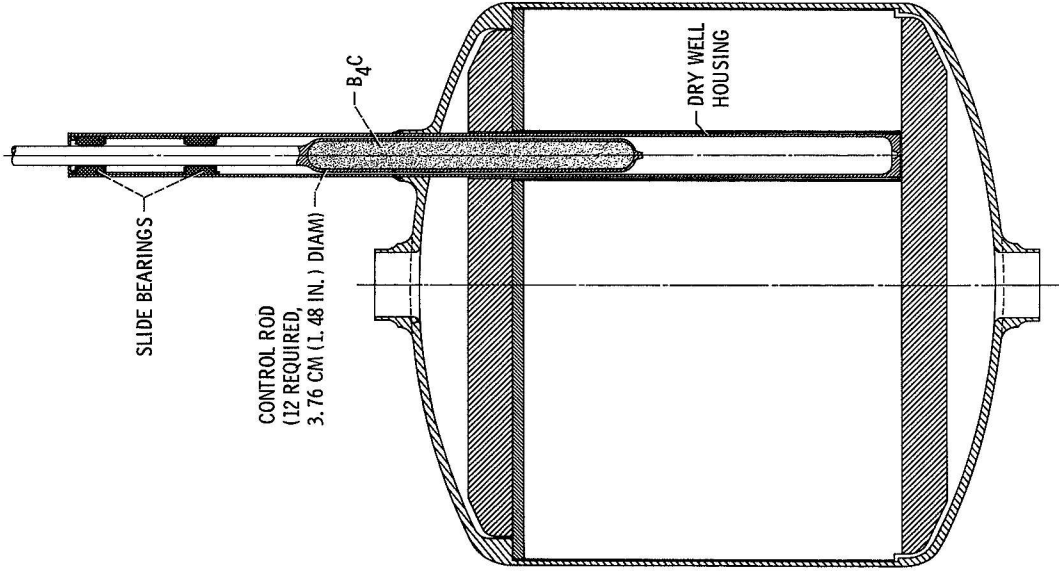


Figure 8. - Alternate control concept- B_4C rods cooled by radiation.

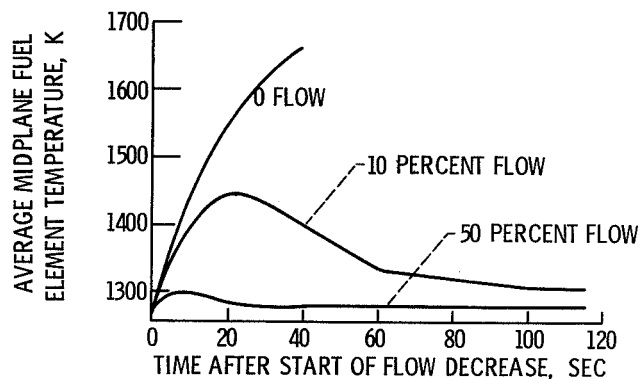


Figure 9. - Fuel element temperatures of various times after decrease in coolant flow from 100 to 50, 10 and 0 percent of design flow.

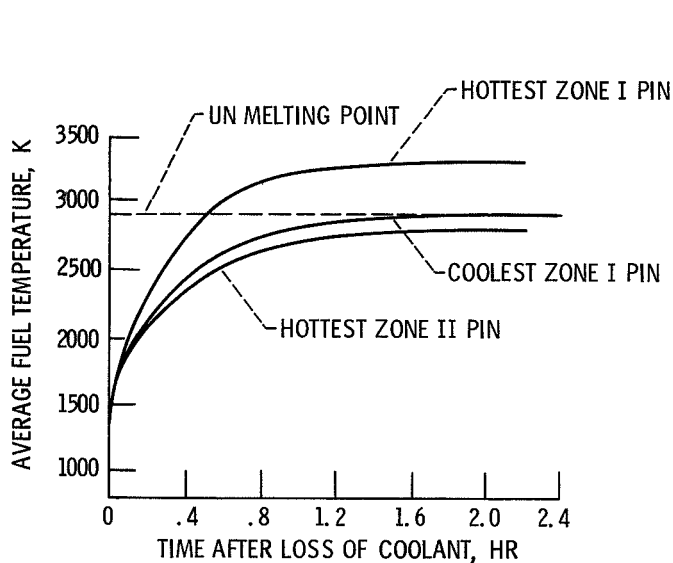


Figure 10. - Average fuel temperature in selected pins as a function of time after loss of coolant. Surface emissivity of 0.20.

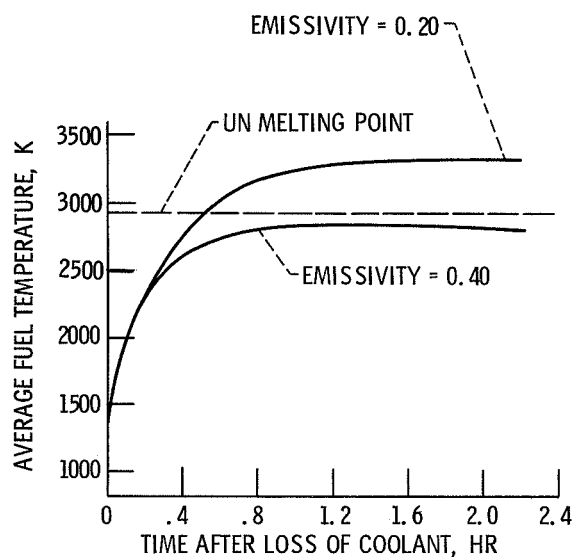


Figure 11. - Average fuel temperature in hottest zone I pin as a function of time after loss of coolant for various surface emissivities.